CHAPTER 18
GAS TURBINE PERFORMANCE CHARACTERISTICS

THERMODYNAMIC PRINCIPLES

The ambient conditions around a gas turbine vary with time and location.[1,2] Standard conditions are required for comparative purposes. The gas turbine industry uses these standard conditions: 59°F (14°C), 14.7 psia (1.013 bar), and 60 percent relative humidity. These conditions are established by the International Organization for Standardization (ISO) and are generally referred to as *ISO Standards.*

Figure 18.1 illustrates a simple-cycle gas turbine. Ambient air enters the compressor of the gas turbine. The pressure increase across the compressor is from 12- to 45-fold. The temperature also increases across the compressor as a result of the compression process. The discharge temperature from the compressor is between 650 and 900°F (345 and 480°C). The air leaving the compressor enters the combustors. The combustion process occurs at almost a constant pressure. In reality, there is a slight decrease in pressure across the combustors. There is significant increase in temperature in the combustors to between 2200 and 3000°F (1200 and 1650°C). The turbine converts the energy in the hot gases to mechanical work. This conversion occurs in two steps. First, the velocity of the hot gases increases in the stationary blades (nozzles) of the turbine. A portion of the thermal energy is converted into kinetic energy (first law of thermodynamics). Second, the rotating blades of the turbine (buckets) convert the kinetic energy to work. The work developed by the turbine drives the compressor and the load. The compressor normally requires from 55 to 67 percent of the total work developed by the turbine.

The single-shaft gas turbine illustrated in Fig. 18.1 has one continuous shaft. Thus, all the components operate at one speed. This design is normally used to drive a generator. It is used for this application because there is no need to vary the speed.

THERMODYNAMIC ANALYSIS

The laws of thermodynamics can be used to analyze the Brayton cycle. Figure 18.2 illustrates the results of this analysis. The cycle efficiency is plotted versus the specific output (output power per pound of airflow) at different firing temperatures (in the combustors) and pressure ratios. The specific output per pound of airflow is an important parameter. The increase in this parameter indicates that the required gas turbine can be smaller for the same output power. Simple-cycle gas turbines [Fig. 18.2 (*a*)] increase in efficiency at a given firing temperature when the pressure ratio increases. Also, the increase in firing temperature results in increase in specific output for a given pressure ratio. The pressure ratio has less

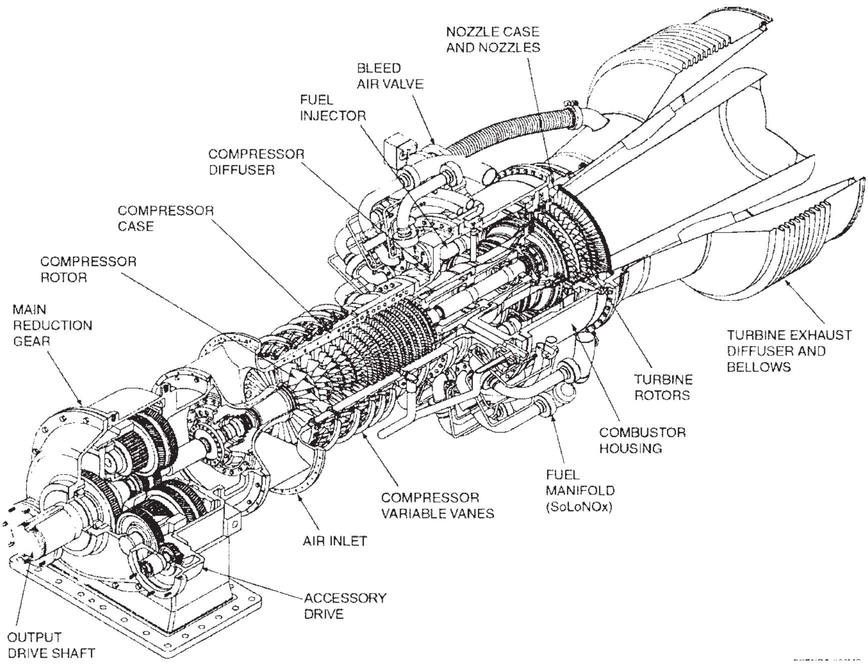

FIGURE 18.1 Cutaway view of the Taurus 70 gas turbine. (*Courtesy of Solar Turbines.*)

effect on efficiency in combined cycles [Fig. 18.2 (*b*)]. The specific output decreases when the pressure ratio increases. The thermal efficiency increases with increasing firing temperature. Note the significant differences between the two curves. The parameters giving optimum performance are different between simple and combined cycles. Increasing the pressure ratio increases the efficiency in simple cycles. Having a relatively modest pressure ratio and higher firing temperature increases the efficiency in combined cycles. For example, the GE MS-7001-FA design parameters are a pressure ratio of 14:1 and a firing temperature of 2350°F (1288°C). The combined-cycle efficiency of this machine is optimized. However, its simple-cycle efficiency is not. On the other hand, the pressure ratio of the LM-6000 is 24:1. Its simple-cycle efficiency is 40 percent.

FACTORS AFFECTING GAS TURBINE PERFORMANCE

The performance of the gas turbine is heavily affected by ambient conditions. Any parameter affecting the mass flow of the air entering the gas turbine will have an impact on the performance of the gas turbine. Figure 18.3 illustrates how the ambient temperature affects the

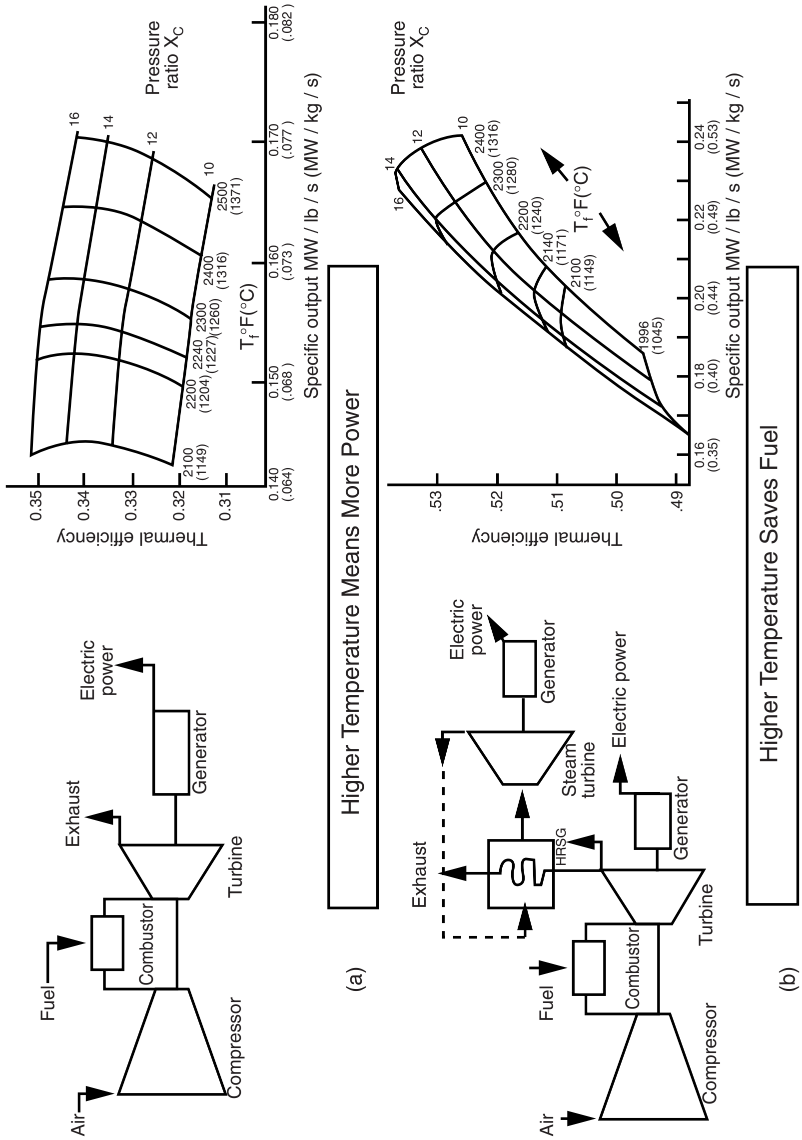

FIGURE 18.2 Gas turbine thermodynamics. (*a*) Simple cycle; (*b*) combined cycle. (*Courtesy of General Electric.*)

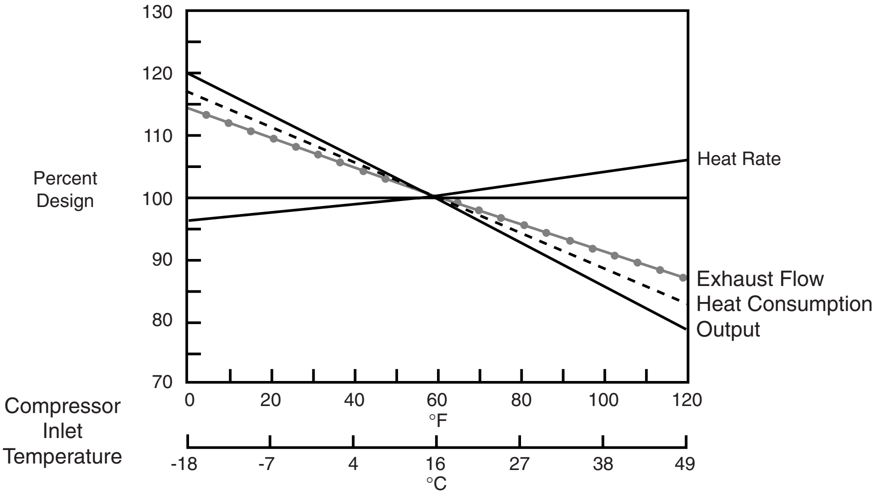

FIGURE 18.3 Effect of ambient temperature. (*Courtesy of General Electric.*)

output power, heat rate (one/(thermal efficiency)), heat consumption, and the exhaust flow for a typical single-shaft heavy-duty gas turbine. The airflow and power output of a gas turbine decrease with increasing altitude due to a decrease in barometric pressure. The reduction in these parameters is proportional to the decrease in the air density. A typical decrease in airflow and output power of a gas turbine is 1 percent per 100-m increase in altitude. The heat rate and the remaining cycle parameters are not affected.

The density of humid air is lower than dry air. An increase in ambient humidity will reduce the power output and efficiency of a gas turbine. An increase in specific humidity of 0.01 kg water vapor/kg dry air will typically reduce the power output and efficiency by 0.0015 and 0.0035 percent, respectively. In the past, this effect was considered negligible. In modern gas turbines, it has a greater significance because the flow of water or steam injected for nitric oxide (NO_X)control is being changed, depending on the level of humidity. This humidity effect is mainly caused by the control system approximation of the firing temperature. Some gas turbine control systems reduce the power when ambient humidity increases. However, on some aeroderivatives, the control system uses the discharge temperature from the gas generator to control the fuel flow. This control system will actually increase the power. The fuel flow is increased to raise the temperature of the moist air (containing humidity) to the setpoint (required temperature). The increase in fuel flow will increase the gas generator speed. (This is a two-spool engine.) The gas generator can operate at different speeds from the power turbine. The increase in fuel flow compensates for the decrease in air density.

Pressure losses in the system are caused by inserting air filtration, silencing, evaporative coolers, chillers in the inlet, or exhaust heat recovery devices. The effects of pressure drop vary with the unit. A pressure drop of 4 in (10 mbar) of water at the inlet to a gas turbine will decrease the output power and efficiency by around 1.5 and 0.5 percent, respectively. The same pressure drop at the exhaust of a gas turbine will reduce the output power and efficiency by around 0.4 percent. The fuel type has an effect on performance. Natural gas produces more output then distillate oil. The difference is almost 2 percent. The reason is that the combustion products of natural gas have higher specific heat. This

is caused by a higher concentration of water vapor resulting from a higher hydrogen-carbon ratio in methane.

The gas turbine performance is affected significantly by gaseous fuels having lower heating values than natural gas. The fuel flow must increase when the heating value drops to provide the required heat. The compressor does not compress the additional mass flow. It increases the turbine and the output power of the machine. The compressor power is not affected by this change. The five side effects include the following:

1. The increase in mass flow through the turbine increases the power developed by the turbine. The compressor takes some of this increase in power. This results in an increase in the pressure ratio across the compressor, driving it closer to the surge limit.
2. The increase in turbine power could take the turbine and all the equipment in the power train above their 100 percent rating. Equipment rated at higher limits may be required in some cases.
3. The size and cost of the fuel piping and valves will increase due to an increase in the volume of the fuel. Coal gases [low or medium heating value (Btu)] are normally supplied at high temperatures. This increases their volumetric flow further.
4. Gases having low heating values (Btu) are normally saturated with water before delivery to the turbine. This results in an increase in the heat transfer coefficients of the combustion products, leading to an increase in the metal temperature in the turbine.
5. The amount of air required to burn the fuel increases as the heating value decreases. Gas turbines having high firing temperatures may not be able to operate using low-heating-value fuel.

As a result of these effects, each model of a gas turbine has a set of application guidelines. They specify the flows, temperatures, and output power to preserve the life of the machine. In most applications involving lower-heating-value fuel, it is assumed that the efficiency and power output will be equal to or higher than the ones obtained using natural gas. In applications involving higher-heating-value fuels, such as refinery gases, the efficiency and output power will be equal to or less than those obtained using natural gas.

Water and steam injection have been used during the last few decades to reduce NO_X emissions. This technique involves injecting water or steam in the cap area, or “head end,” of the combustor liner. The output power and efficiency will increase due to the additional mass flow. However, each machine has limits on the amount of water or steam injected. These are imposed to protect the combustor and turbine section. Steam injection can increase the output power and efficiency by 20 and 10 percent, respectively. Water injection can increase the output power by 10 percent. However, it has very little effect on efficiency because more fuel is needed to raise the water to combustor temperature.

AIR EXTRACTION

Some gas turbine applications require air from the compressor. In general, up to 5 percent of the flow can be extracted from the discharge casing of the compressor. This can be done without modification to the casings or on-base piping. Higher flow (from 16 to 20 percent) can be extracted from the compressor. However, this requires modifications to the casings, piping, and controls. Air extraction has a significant effect on the performance of the machine. The rule of thumb is that every 1 percent of air extraction causes 2 percent of reduction in power output.

PERFORMANCE ENHANCEMENTS

Two possibilities can be considered to enhance the performance when additional power is required:

1. Inlet cooling
2. Steam and water injection for power augmentation

Inlet Cooling

Figure 18.3 shows that there is an improvement in power output and heat rate when the inlet temperature to the compressor decreases. The installation of an evaporative cooler or inlet chiller in the inlet ducting (downstream of the inlet filters) will lower the inlet temperature to the compressor. Inadequate operation of this equipment can result in condensation or carryover of water into the compressor. This increases compressor fouling and degrades the performance. Moisture separators, or coalescing pads, are generally installed to reduce the possibility of moisture carryover. Figure 18.4 illustrates the effect of evaporative cooling on power output and heat rate. It indicates that hot, low-humidity climates gain the most from evaporative cooling. It should be noted that evaporative cooling is limited to an ambient temperature higher than 59°F (15°C). The reason is concern about potential formation of ice on the compressor blades. The information presented in Fig. 18.4 is based on the evaporative cooler having an effectiveness of 85 percent. The effectiveness is measured by how close the cooler exit temperature is to the ambient wet-bulb temperature. For most applications, a cooler effectiveness of between 85 and 90 percent provides the most economic benefit.

Chillers do not have the same characteristics as evaporative coolers. The wet-bulb temperature does not limit them. The temperature achieved is limited by the capacity of the chiller.

Steam and Water Injection for Power Augmentation

The injection of steam or water into the combustor to reduce NO_X emissions results in increasing the mass flow. Therefore, the power output will increase. The amount of steam

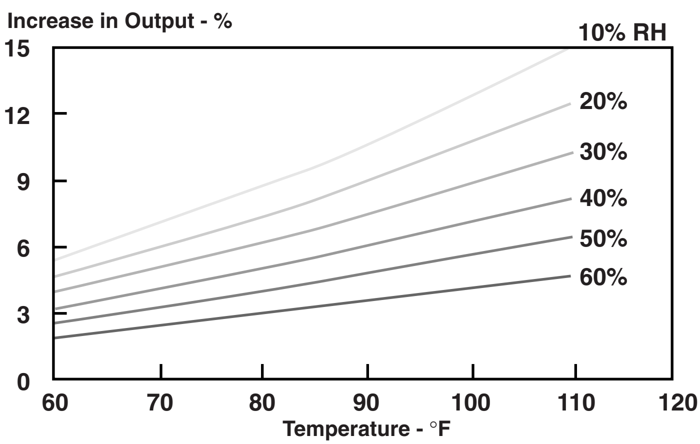

FIGURE 18.4 Effect of evaporative cooling on output and heat rate.

or water injected is limited to the amount required to meet the NO_X requirement. It is around 1.1 kg of steam/1 kg of fuel or 1 kg of water/1 kg of fuel.

Steam injection was used for power augmentation for more than 30 years. The steam is normally injected into the compressor discharge casing and combustor. It can increase the power output by up to 20 percent and the efficiency by 10 percent. Most machines are designed to allow up to 5 percent of the compressor airflow for steam injection. The steam must have around 50°F (28°C) superheat. It is normally premixed with the fuel before being injected in the combustor.

PEAK RATING

The performance values for a machine are normally given for base load ratings. The American National Standards Institute (ANSI) B133.6 Ratings and Performance[3] define the following:

- *Base load.* Operation of 8000 h/year with 800 h per start
- *Peak load.* Operation of 1250 h/year with 5 h per start

Since the peak-load operating hours are shorter, increasing the firing temperature can increase the power output. This mode of operation requires shorter inspection intervals. Despite this penalty, running a gas turbine at peak could be a cost-effective way of operation. Additional power is generated in periods of higher power cost. Generators also have peak ratings. These are obtained by operating at a higher power factor or temperature increase. The ratings of the peak cycle are customized to the turbine mission. They consider the starts and hours of operation. The firing temperature can be selected between the base and the peak. They are chosen to maximize the power output while remaining within the limits of the repair interval of the turbine hot section. For example, a typical heavy-duty gas turbine can operate for 24,000 h using gas fuel at base load. The hot-section repair interval is limited to 800 starts. The hot-section repair interval is also limited to 4000 h for peaking cycle of 5 h per start. This corresponds to a peak firing temperature operation. Turbine missions between 5 and 800 h per start will allow the firing temperature to increase above the base temperature. However, the firing temperature will remain below the peak temperature. This can be done without sacrificing time to the repair of the hot section. The water injection for power augmentation can also be factored into the rating of the peak cycle to further increase the power output.

PERFORMANCE DEGRADATION

The performance of all turbomachinery degrades with time. There are two types of degradation in gas turbines: recoverable and nonrecoverable loss. The compressor fouling is a recoverable loss. It can be recovered partially by water washing. This loss can be recovered fully by mechanical cleaning of the compressor blades and vanes after opening the unit. The increase in turbine and compressor clearances is a nonrecoverable loss. The changes in surface finish and airfoil contours are also nonrecoverable. This loss can only be recovered by replacement of the affected parts. After 24,000 h of operation (the normal recommended interval for inspection of the hot gas path), the total performance degradation is between 1 and 1.5 percent. Recent industrial experience shows that frequent off-line water washing will reduce the recoverable and nonrecoverable losses. In general, the machines that operate in hot, dry climates degrade less than those in humid climates.

VERIFYING GAS TURBINE PERFORMANCE

A performance test is normally conducted after the gas turbine is installed. The power, fuel, heat consumption, and so forth are recorded. This is done to allow these parameters to be corrected to the condition of the guarantee. The ASME Performance Test Code PTC-22-1985, "Gas Turbine Plants,"[4] describes the testing procedures and calculation methods. All the instruments used for data collection must be inspected and calibrated before the test.

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